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Evolution of Popponesset Beach and Its Effect on Popponesset Bay

by Mary A. Cialone
Coastal Engineering Research Center

WES

Prepared for U.S. Army Engineer Division, New England

Coastal Research Program

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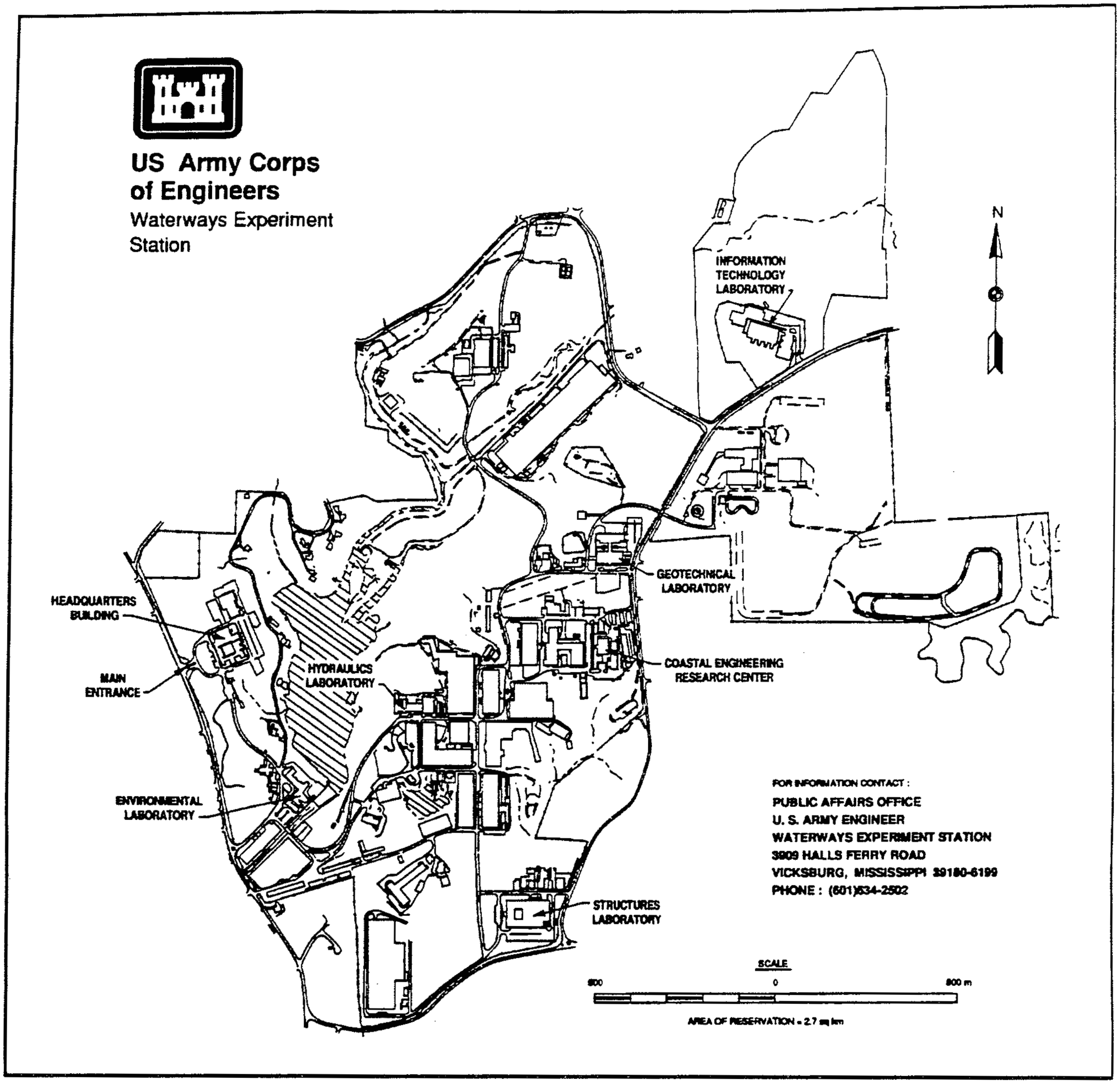

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Preface

This study was authorized by the U.S. Army Engineer Division, New England, and conducted at the Coastal Engineering Research Center (CERC) of the U.S. Army Engineer Waterways Experiment Station (WES). The study was conducted and this report was prepared during the period September-December 1992 by Ms. Mary A. Cialone, Research Division (RD), CERC, under the supervision of Mr. Bruce A. Ebersole, Chief, Coastal Processes Branch, and Mr. H. Lee Butler, Chief, RD. General supervision was provided by Dr. James R. Houston, Director, CERC, and Mr. Charles C. Calhoun, Jr., Assistant Director, CERC.

The main purpose of the study was to determine the likelihood of a breach of Popponesset Spit and the impact (in terms of water quality, storm protection, and navigation) of breaching and/or slow degradation of the spit on Popponesset Bay. A review of historical information pertaining to the Popponesset Beach area and an analytical/empirical "desktop" analysis were performed.

At the time of publication of this report Dr. Robert W. Whalin was Director of WES. COL Bruce K. Howard, EN, was Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4046.873	square meters
cubic feet	0.02831685	cubic meters
cubic yards	0.7646	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1.6093	kilometers
square feet	0.09290304	square meters

1 Introduction

The purpose of this study is to answer the following questions: (a) will a major breach of Popponesset Beach occur, and if so, under what conditions, and (b) how will breaching and/or slow degradation of the entire barrier beach affect water quality, storm protection, and navigation in the bay? The findings in this report are based on review of historical information pertaining to the Popponesset Beach area, and subsequent analytical/empirical "desktop" analyses.

This report is organized in the following fashion: Chapter 1 introduces the study area and reviews available historical data; Chapter 2 discusses the evolution of Popponesset Beach and storm hydraulics; Chapter 3 covers an analysis of inlet stability; Chapter 4 discusses modes of deterioration of Popponesset Spit and the impacts on navigation, storm protection, and water quality in Popponesset Bay; Chapter 5 discusses possible solutions to the problem of deterioration of Popponesset Beach; Chapter 6 suggests additional information needed to further define the situation at Popponesset Beach and addresses studies which could be conducted to evaluate various solution schemes; and Chapter 7 provides conclusions drawn from the study.

Study Area

Popponesset Beach is an approximately 1-mile-long[1] barrier beach (or spit) fronting Popponesset Bay located on Nantucket Sound in Mashpee, Cape Cod, Massachusetts (Figure 1). Net longshore transport is to the northeast in the Popponesset Spit littoral cell, which extends from Succonnesset Point (to the west) to the tip of the spit and offshore to Succonnesset Shoals. A series of groins west of the spit were constructed in the 1950's to stabilize the shoreline. The groins have probably limited sediment supply to Popponesset Spit to some degree; however, most of the groins are short and sediment is likely to bypass them under storm conditions because of the wider surf zone. The spit extends in a northeasterly direction from the town of Popponesset to its terminus at the inlet entrance near Meadow Point (Figure 2). The inlet leads

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vi.

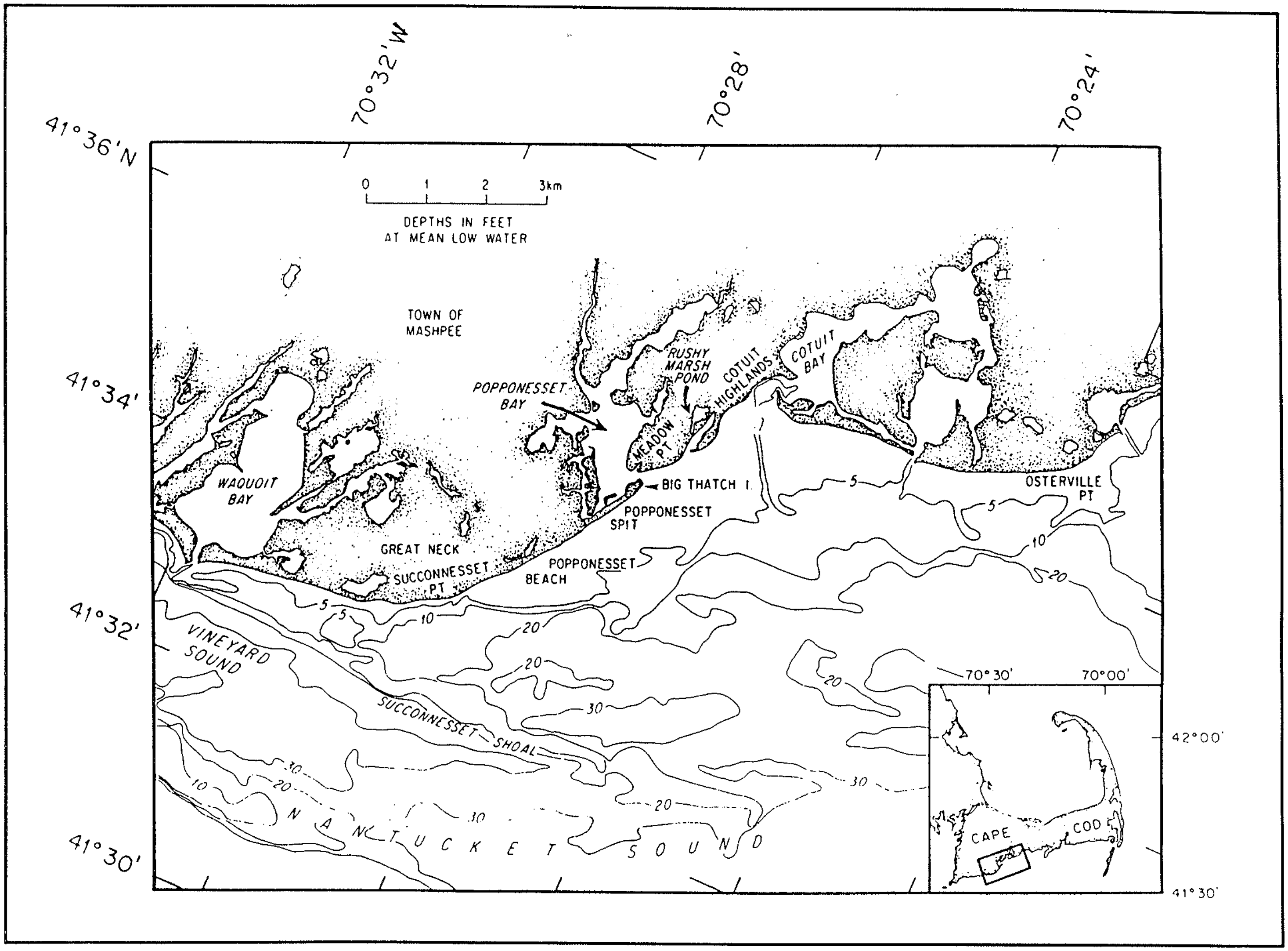


Figure 1. Location map from Aubrey and Gaines (1982b)

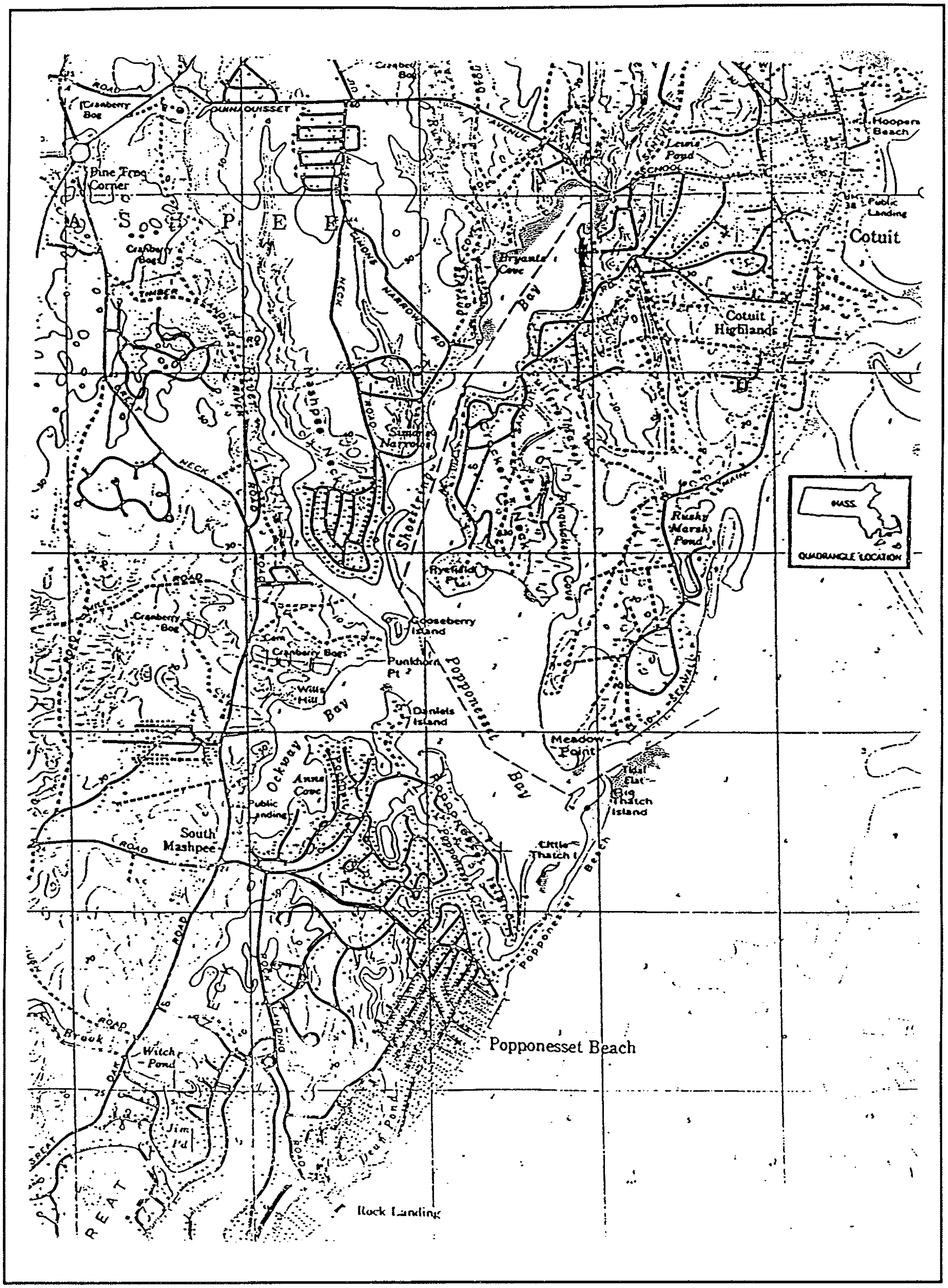


Figure 2. The study area

to Popponesset Bay, which is a shallow, saltwater lagoon covering approximately 665 acres. The mean tide range in the bay is 2.3 ft and the spring tide range is 2.8 ft. The bay is usually sheltered from direct wave and storm attack by the barrier beach and is used for shellfishing and recreational boating. However, the decreasing elevation along the entire length of the barrier spit and the decreasing width near its base are limiting the spit's ability to shelter the area behind it from more frequent (less severe) storm events. Popponesset Island (Figure 2), located directly behind the base of the spit, is a critical factor in the study from a storm protection standpoint as well as a navigation standpoint. Washover during storms tends to constrict the navigation channel around the southern tip of Popponesset Island, limiting or blocking navigation, and homes on Popponesset Island have been flooded during severe storms. Three major dredging projects were conducted in 1916, 1936, and 1961, as well as minor dredging projects in 1986 and 1991 to improve navigation in the bay and in the approach to Popponesset Creek.

Available Historical Data

Maps, charts, and aerial photographs of Popponesset Beach were used to assemble a picture of spit evolution from 1787 to the present (Aubrey and Gaines 1982a) (Figures 3-6). Aubrey and Gaines analyzed 92 charts and maps (1670-1979) and 43 aerial photographs (1938-1981); however, representation of coastal features is not rigorous in the early maps (1670-1857). More recent aerial photographs (1984 and 1991) provided additional information on spit evolution. It is interesting to note that the early shoreline illustration (1831) is similar in length and inlet configuration to present conditions.

Cross-section views (or profiles) of Popponesset Spit are available for 1966 and 1991 (Figure 7). The source of this information is the Director of Engineering for the New Seabury Company Ltd., Michael H. Grotzke. From this figure one observes that the peak elevation has diminished from 13.5 to 6 ft National Geodetic Vertical Datum (NGVD) (mean low water (mlw) = -0.7 NGVD), the spit has migrated landward, and the width of the spit has been reduced dramatically.

Water levels for several storms (Hurricane Carol ('54), Hurricane Donna ('60), Hurricane Bob ('91), 1938, 1944, and 1956 hurricanes, the Blizzard of '78 and the Halloween northeaster ('91)) as well as predicted water levels for 1-, 10-, 50-, and 100-year storms are given in Figure 8 (U.S. Army Engineer Division, New England 1988). Most of the recorded water levels for these storms indicate that they are approximately 5- to 10-year events, with the exceptions of Hurricane Carol (35- or 40-year event), and the 1944 hurricane (nearly a 100-year event).

Two islands, Martha's Vineyard and Nantucket Island, and shallow shoals are located offshore from the spit and serve to limit wave energy in the study area. Wave measurements in Nantucket Sound are not available; however,

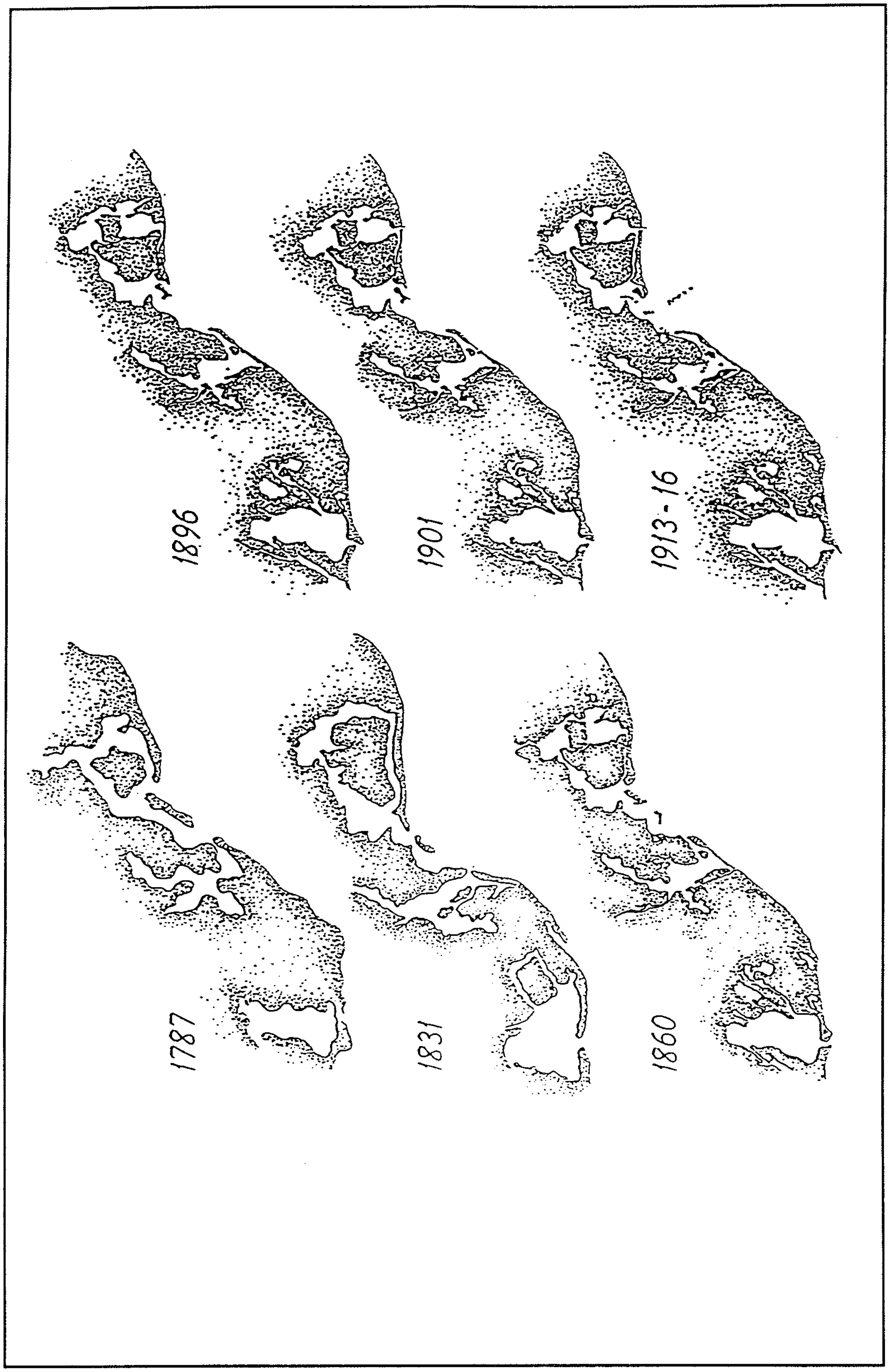


Figure 3. Spit evolution (1787-1916) from Aubrey and Gaines (1982a)

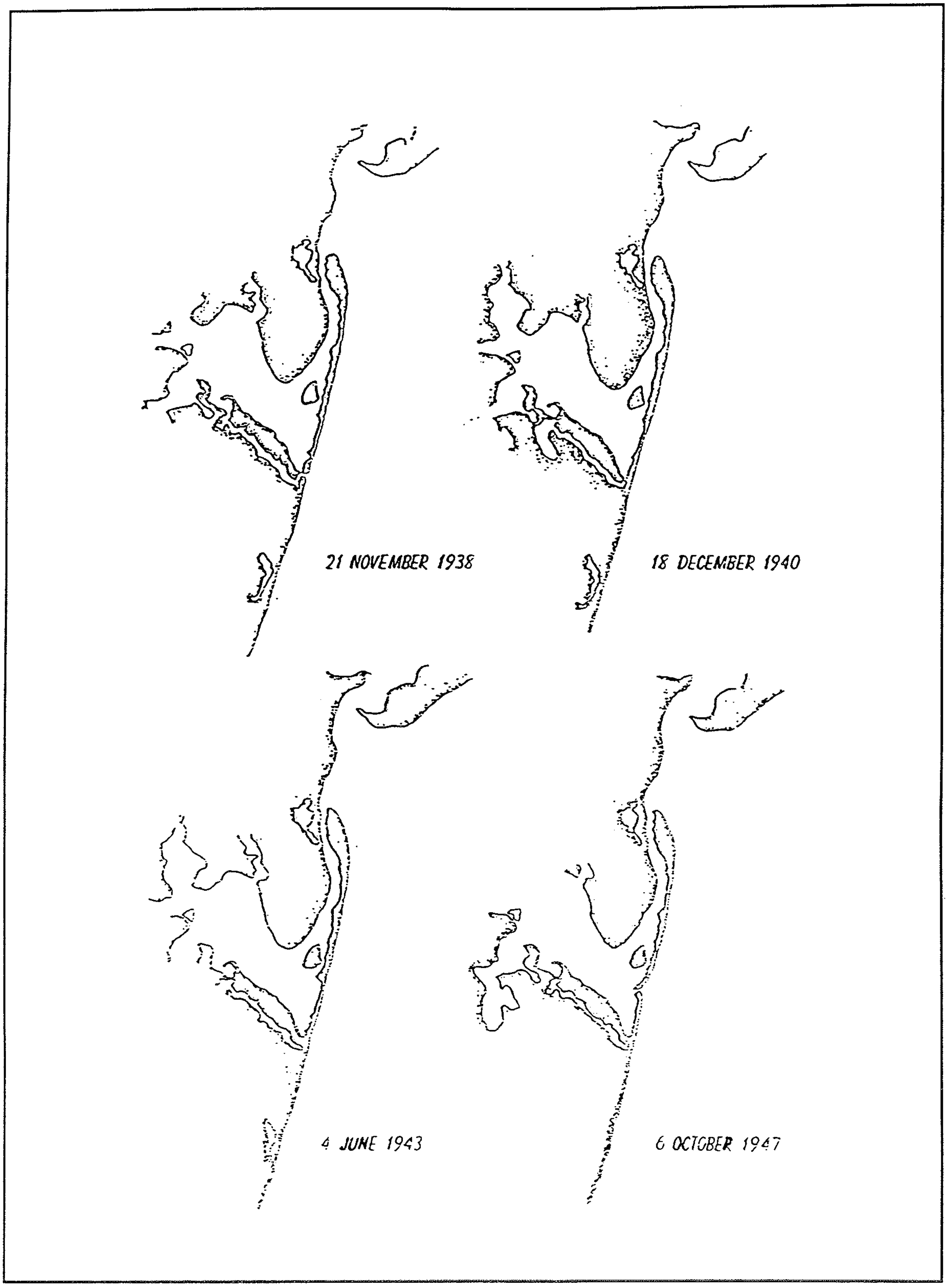


Figure 4. Spit evolution (1938-1947) from Aubrey and Gaines (1982a)

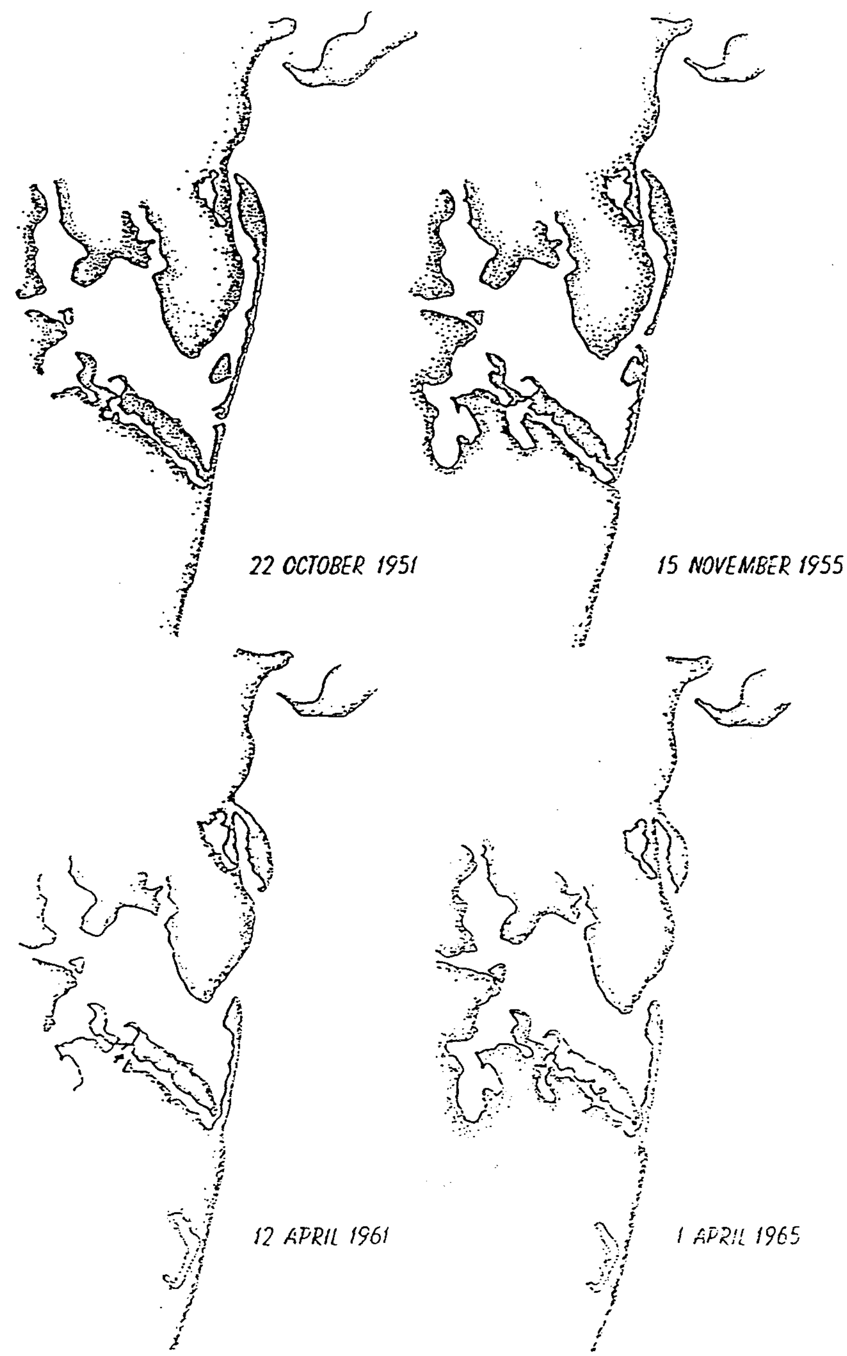


Figure 5. Spit evolution (1951-1965) from Aubrey and Gaines (1982a)

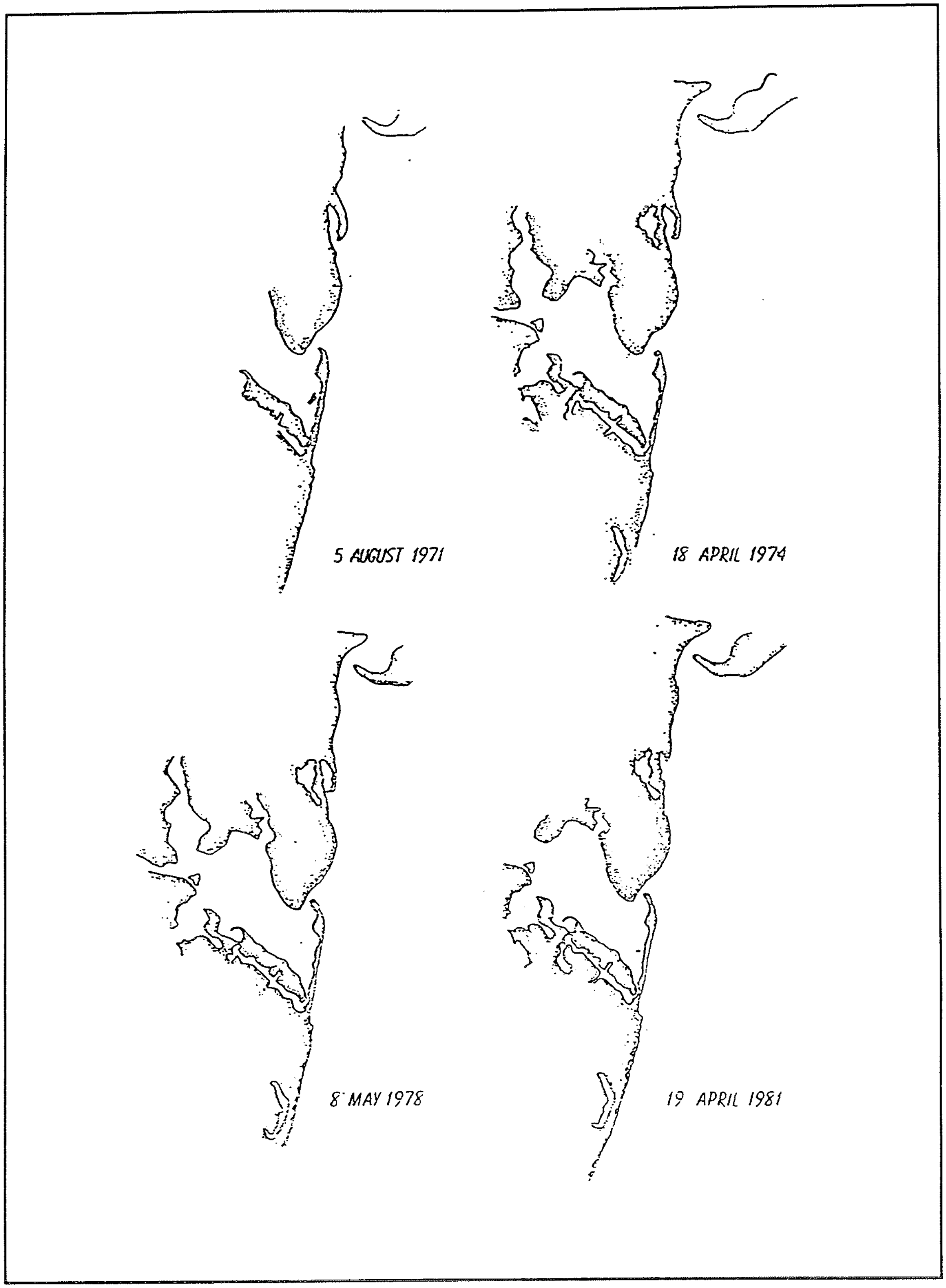


Figure 6. Spit evolution (1971-1981) from Aubrey and Gaines (1982a)

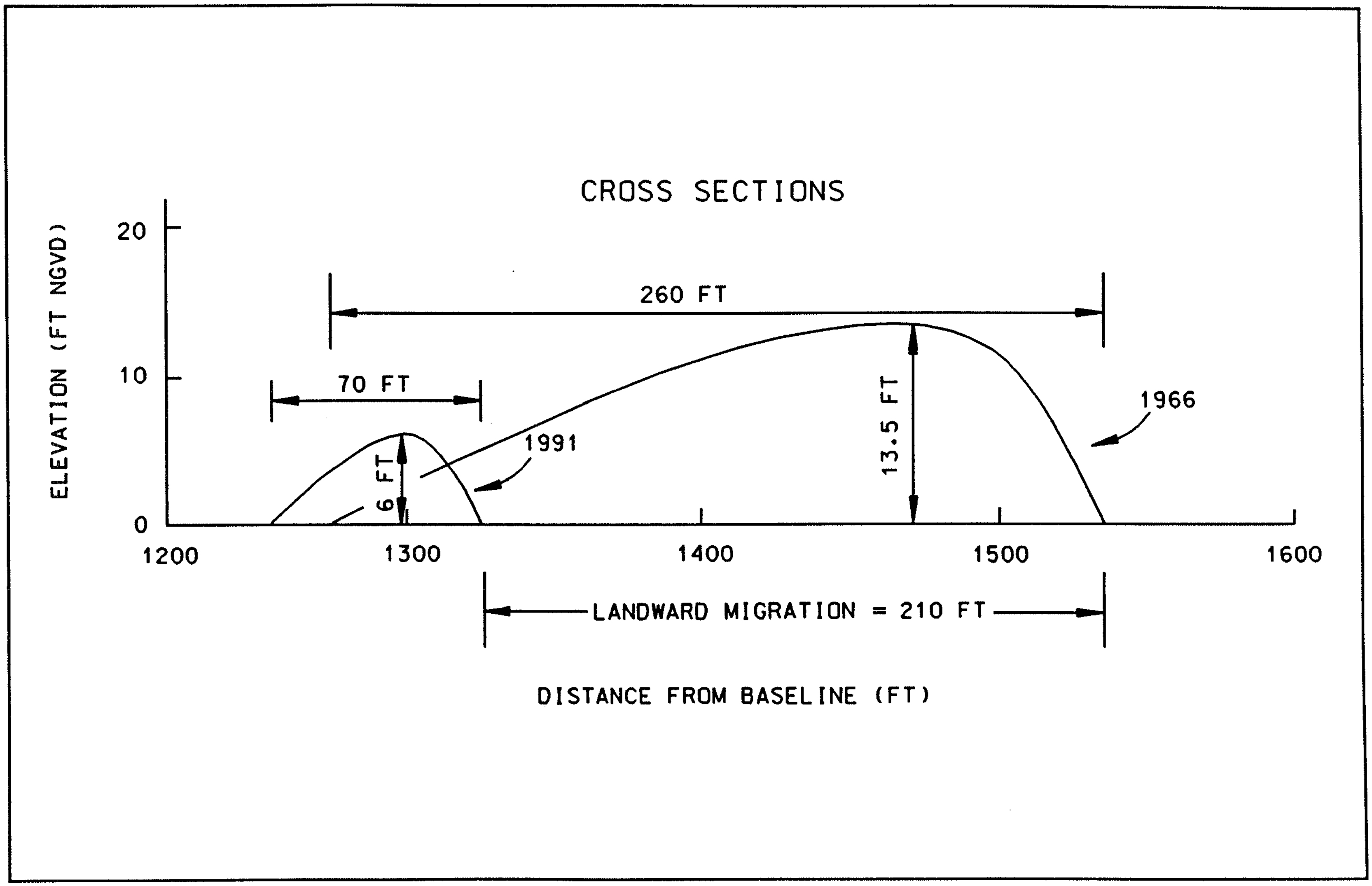


Figure 7. Cross sections (1966 and 1991) of Popponesset Spit

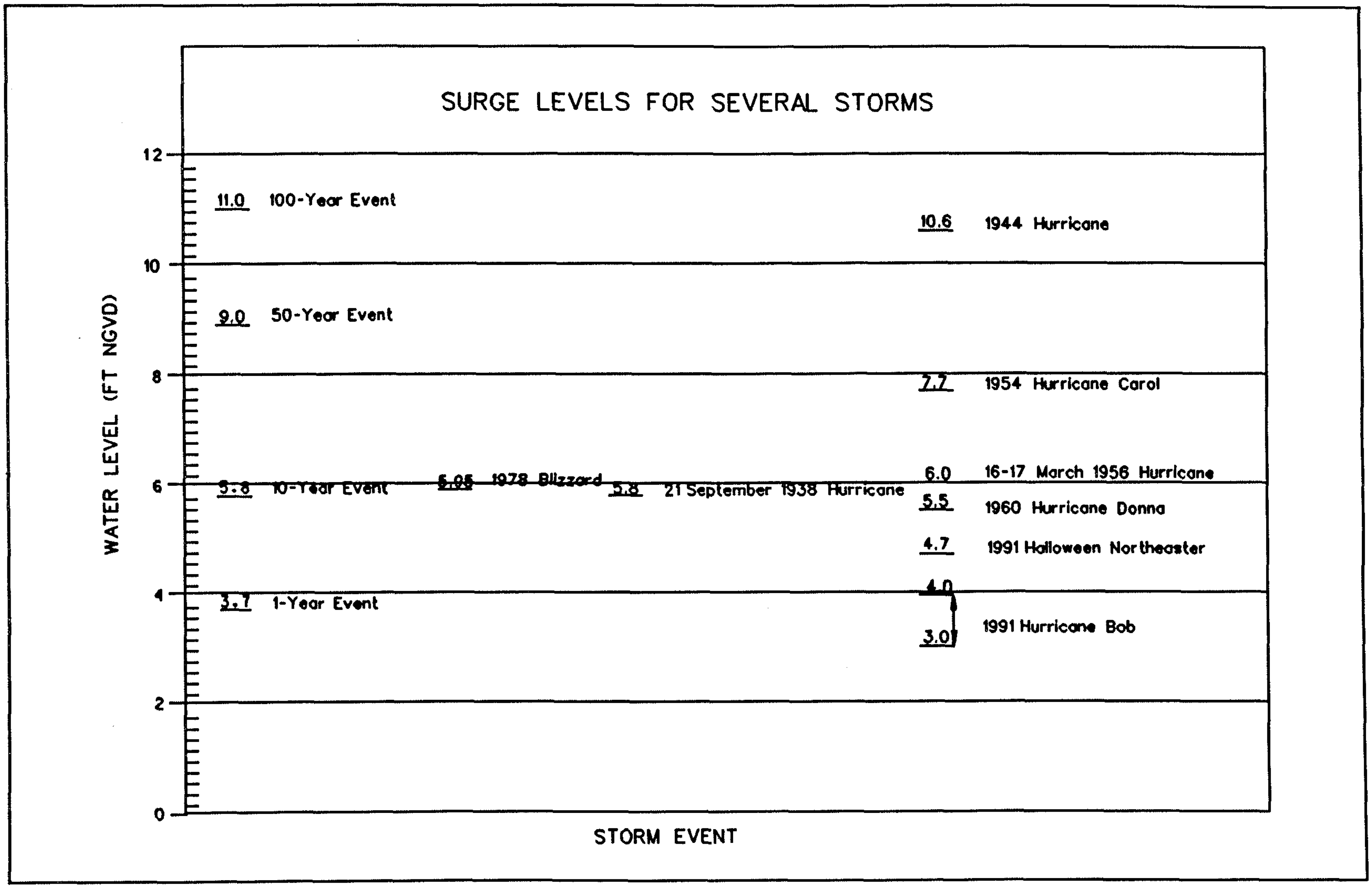


Figure 8. Storm surge levels

the Wave Information Study (WIS) Station 86 is located seaward of Martha's Vineyard and the mean wave height from the 1956 to 1975 WIS hindcast for Station 86 is from 3 to 5 ft (1 to 1.5 m) (Hubertz et al. 1992). Wave heights in the sheltered area behind Martha's Vineyard are observed to be much smaller. Peak direction of waves at Station 86 is from the south 23 percent of the time and from the SSW to SSE band 53 percent of the time. Maximum wave conditions at Station 86 indicate wave heights from 10 to 21 ft (3 to 6.4 m) with associated periods of 10 to 14 sec. Maximum tidal velocities are estimated to be 2.0 fps in the entrance channel to Popponesset Bay and 1.0 fps in the entrance to Popponesset Creek at the southern tip of Popponesset Island.

Channels were dredged in Popponesset Bay in 1916 and 1936 and are observed on the 1938 aerial photograph. An unknown amount of dredged material from the 1916 project was deposited at an unidentified location along "the western shore." Details of the 1936 project were not specified. In 1961, channel dredging produced 140,000 cu yd of material which was placed on Popponesset Spit near Big Thatch Island and on the shore of Popponesset Creek (Figure 2) and Popponesset Island. In 1986, the entrance channel to Popponesset Bay was dredged to a depth of 5.7 ft NGVD (6.4 ft mlw) and a width of 80 ft, yielding 12,000 cu yd of dredged material placed on Popponesset Beach. In 1991, the overwash from Hurricane Bob effectively blocked navigation between Popponesset Creek and Popponesset Bay. An estimated 3,000-4,000 cu yd of dredged material was removed from the channel and deposited on Popponesset Spit, closing a 30-ft-wide breach near Popponesset Island.

Popponesset Spit has experienced dramatic changes in the last 40 years, beginning with a major breach in 1954, which resulted from a series of hurricanes (Carol, Edna, and Hazel). Historical data on breaches of Popponesset Spit were obtained from aerial photographs, past reports, and conversations with residents. Breaches near Popponesset Island, Little Thatch Island, and Big Thatch Island were observed at various times between 1892 and 1991 (Table 1). Details of Popponesset Spit evolution and breach formation, and analysis of available data are given in Chapters 2 and 3.

Table 1
History of Breaches of Popponesset Spit

Year	Location
1892	Little Thatch Island
1893	Big Thatch Island (west side)
1896	Big Thatch Island (west side)
1901	Big Thatch Island (west side)
1910	Big Thatch Island (west side)
1914-1917	Big Thatch Island (west side)
1931	Popponesset Island
1932	Popponesset Island
1936	Popponesset Island
1938	Popponesset Island
1947	Little Thatch Island
1949	Little Thatch Island
1951	Little Thatch Island
1955	Big Thatch Island/Popponesset Island
1970's	Big Thatch Island (Station G)
1991	Popponesset Island

2 Evolution of Popponesset Spit and Storm Hydraulics

Popponesset Spit has undergone considerable transformation during the past two centuries. These changes include growth and attrition in length, landward migration and rotation, narrowing, diminished elevation, and opening and closing of breaches. The evolution of Popponesset Spit is the sum of all of these changes as discussed below. In this section, processes such as storm surge, runup, overwash, and longshore sediment transport are also discussed and analyzed in terms of their effect on spit degradation and breaching.

Growth and Attrition

From early illustrations, Popponesset Spit appeared to be stable in length through the mid-1800's. Interestingly, that length is similar to what is observed today. In the mid-1800's, the spit began to elongate, passing Meadow Point. Popponesset Spit continued to increase in length during the time period 1850-1954, reaching Rushy Point Pond and a maximum length of 1.7 miles. In 1954, a series of three hurricanes (Carol, Edna, and Hazel) caused a major breach of the spit, dividing it into two nearly equal limbs. The breach occurred at the location which appeared to be the stable inlet location prior to 1850. The landward migration of the upper (northeast) limb filled the old navigation channel, gradually diminishing the limb and closing the old inlet. The southwest limb (Popponesset Spit) has not changed appreciably in length (0.8 mile).

Landward Migration

Quantification of shoreline change was accomplished by Aubrey and Gaines (1982a) by establishing a baseline between well-defined, permanent features and running the baseline parallel to Popponesset Spit for all aerial photographs (Figure 9). Stations F and G traverse Popponesset Spit. This work was extended to include the 1984 and 1991 aerial photographs in the data analysis; however, the locations of Stations F and G could not be obtained precisely. The spit has migrated landward 395-665 ft (120-200 m) since 1938 and has

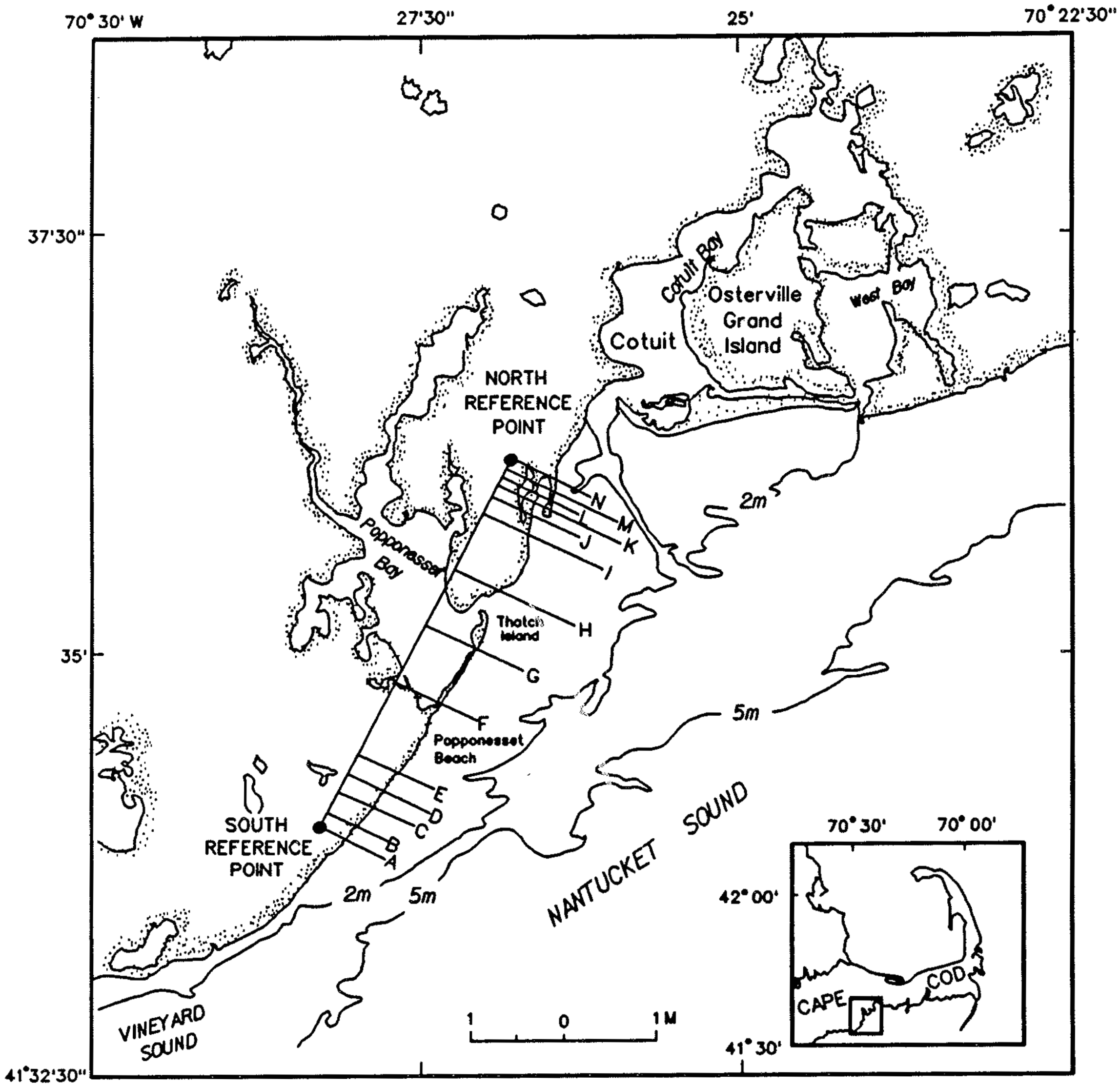


Figure 9. Baseline and station lines for shoreline measurements (Aubrey and Gaines 1982a)

rotated about its base in a counterclockwise direction (Figure 10). The spit rotation stems from the fact that the groin at the base of the spit anchors the shoreline, pinning its location. The landward migration is dominated by major storms (1954, 1978, 1991) depicted by large changes in slope and the long-term landward migration occurs at a slower rate (Figure 11). More than half of the shoreward migration of Station G appears to be associated with major storms, a quantity added to the more regular shoreline retreat of 5 ft/year (1.5 m/year) at this station. At Station F (near Popponesset Island) average shoreward migration is only 0.3 ft/year (0.1 m/year) before 1954 and 0.7 ft/year (0.3 m/year) after 1954. The series of 1954 hurricanes, however, translated the shoreline about 165 ft (50 m) landward which far exceeds the average value. The shoreline was displaced an additional 100 ft (30 m) between the time of the 1984 aerial photograph and the 1991 (post Hurricane Bob) aerial photograph. The overall trend shows less retreat at Station F than at Station G, which is consistent with the rotation of the spit and the proximity of Station F to the groins.

Width of Popponesset Spit

The width of the barrier beach was measured from 1938, 1966, 1984, and 1991 aerial photographs and these values were added (as X's) to the figure of beach widths obtained by Aubrey and Gaines (Figure 12). The discrepancy in the 1966 beach width is most probably due to uncertainty in the exact location of Stations F and G. At Stations F and G the beach width has decreased dramatically in recent years. Several factors may contribute to this phenomenon. Overwash events tend to roll material over the spit and the entire feature attempts to migrate landward. Channel dredging between Popponesset Spit and Popponesset Island limits any further landward movement of the bay-side shoreline of the spit. With the bay-side boundary pinned and the seaward boundary moving landward, thinning of the spit is inevitable.

Diminished Elevation

In 1966, the spit had a 500-ft-long ridge with a peak elevation of 13.5 ft NGVD. As of 1991, the peak elevation of Popponesset Spit was 6 ft NGVD (Figure 7) as reported by the New Seabury Co. Ltd. The peak elevation observed during a 1992 walking tour was approximately 5 ft NGVD and it is reported by Grotzke[1] that the most recent storm (December 1992) lowered the peak elevation even further. The reduction in peak elevation indicates that a less severe storm can now completely submerge the spit. Whereas a 10-year event in 1966 could cause breaching to occur, a 10-year event now would

[1] Personal Communication, 14 December 1992, Michael H. Grotzke, Director of Engineering, New Seabury Company Ltd., New Seabury, MA.

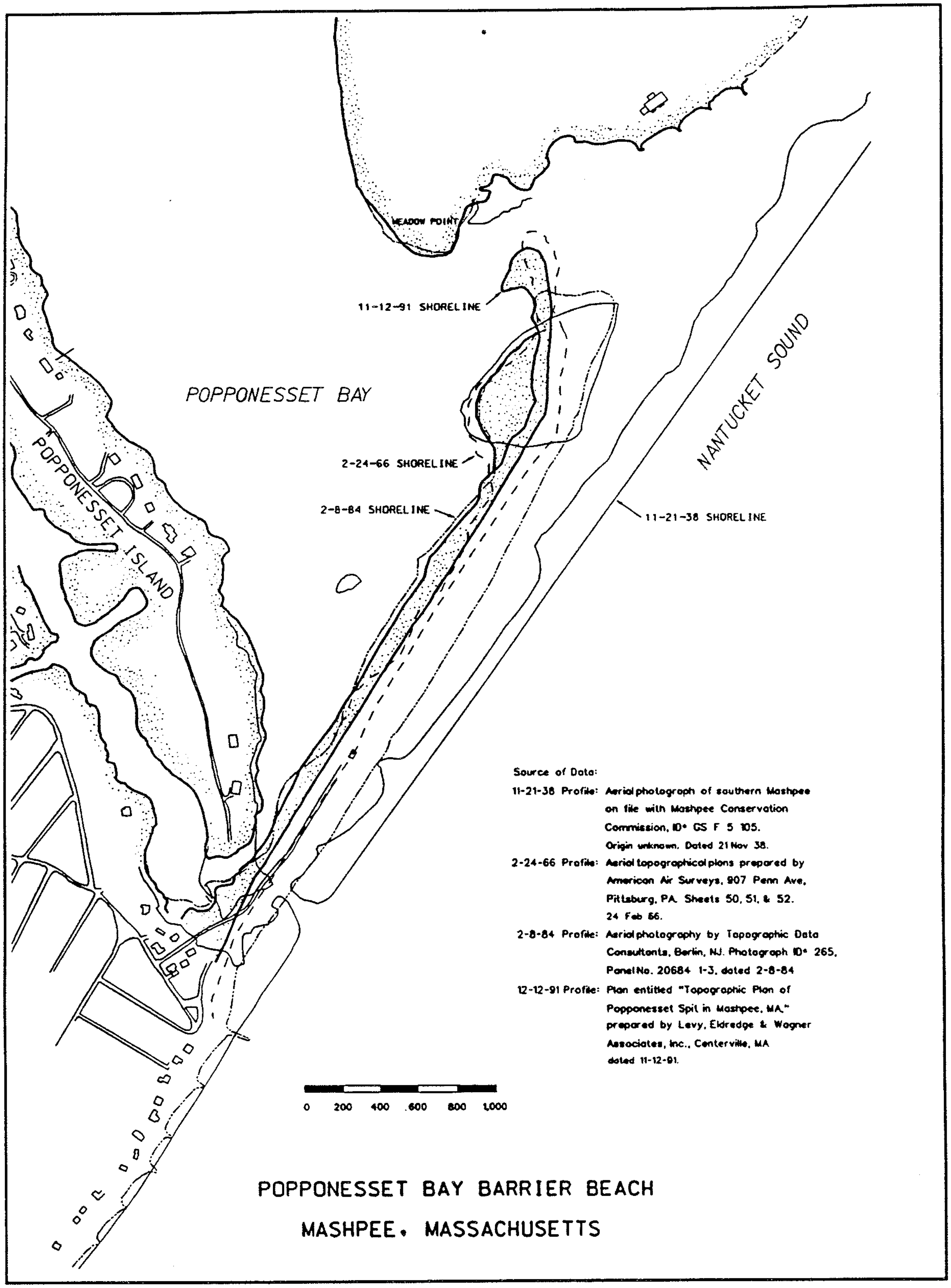


Figure 10. Compilation of aerial photographs

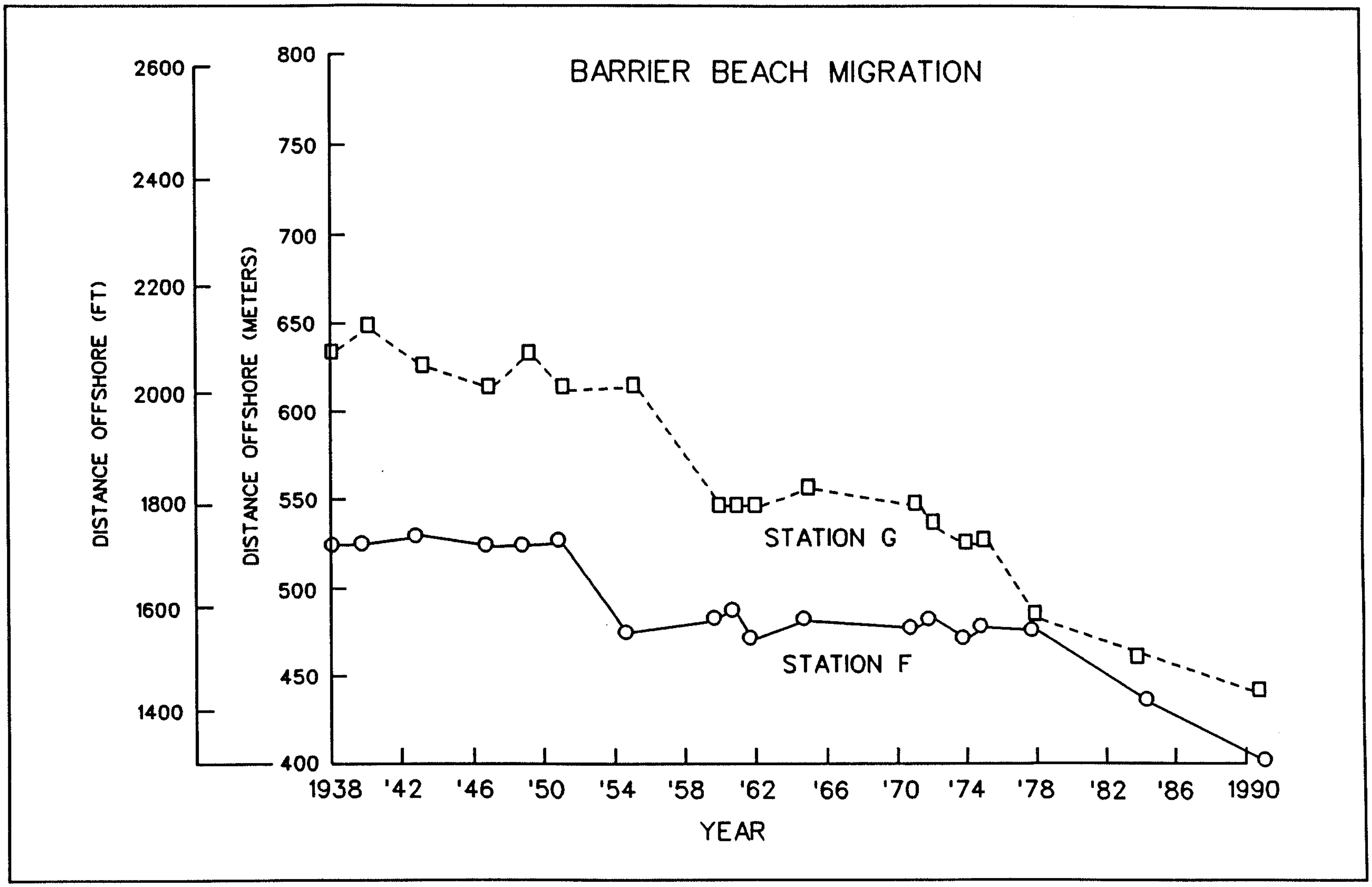


Figure 11. Shoreline position for Popponesset Spit stations adapted from Aubrey and Gaines (1982a)

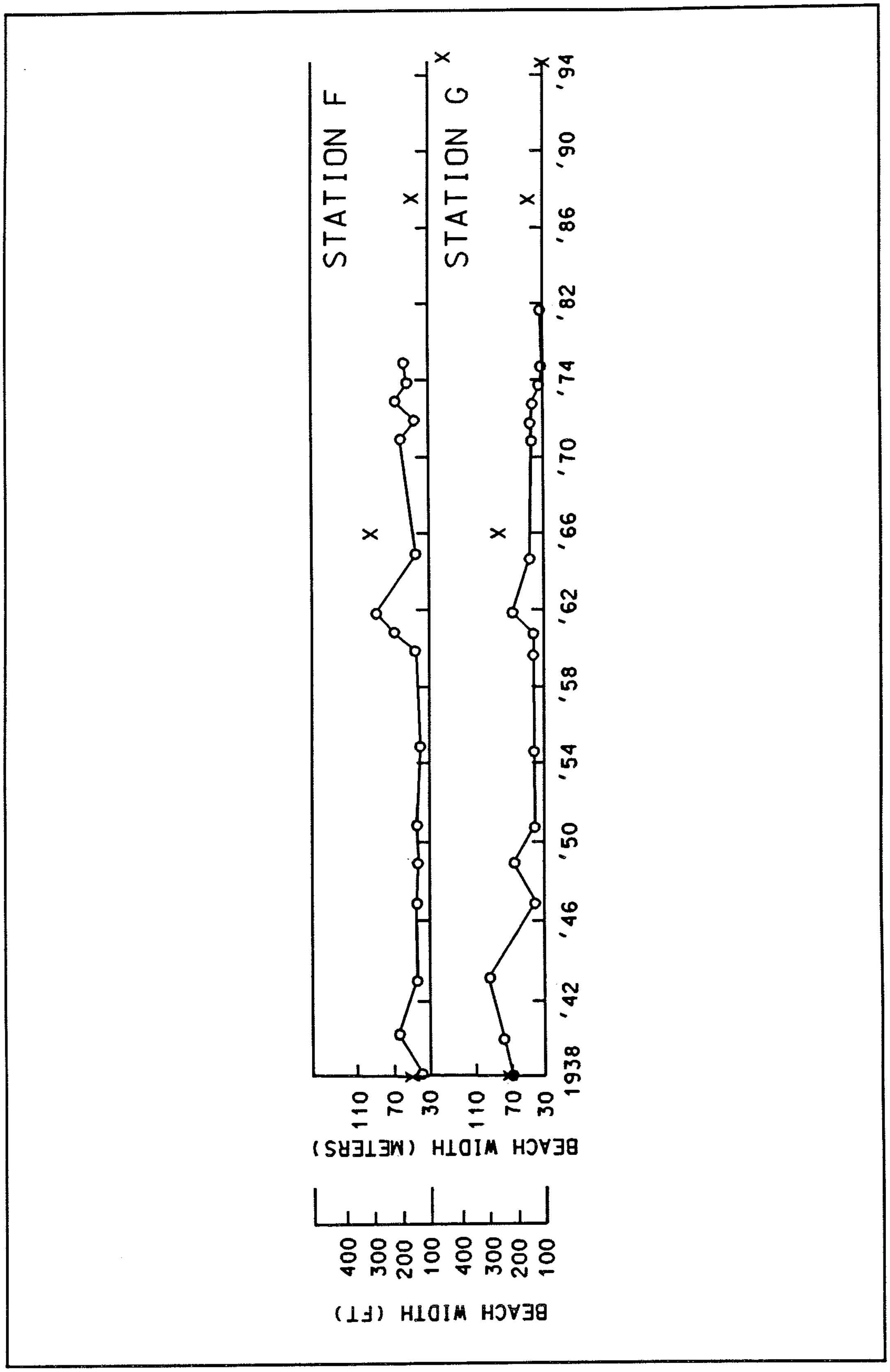


Figure 12. Beach width for Popponesset Spit stations adapted from Aubrey and Gaines (1982a)

probably submerge the entire spit allowing more energy to reach the interior shoreline. Diminished elevation and reduced width are key factors to the evolution of Popponesset Spit.

Breaches

Popponesset Spit has been breached several times in the last 200 years, with a major breach occurring in 1954 (Table 1). A breach was evident near Popponesset Island in the 1938 aerial photograph; however, by 1940 the breach was closed (Figure 4). The 1947 and 1951 aerial photographs show a breach to the west of Little Thatch Island, but it was closed by 1955 (Figures 4 and 5). The location of the 1954 breach appeared to be the stable inlet location prior to 1850 (Figure 5). The breach occurred near the base of the main inlet channel and provided a more hydraulically efficient path for tidal exchange. This suggests that the present inlet location is, in fact, the most hydraulically efficient location. As quoted from Fitzgerald (1988),

> ... the migration of a tidal inlet often results in an elongation of the inlet channel. This process produces increasingly inefficient tidal flow between the ocean and bay. Under these conditions if the updrift spit is breached during a catastrophic storm, the new inlet which provides a shorter route for tidal exchange will normally stay open while the less efficient old inlet gradually closes. This process is well illustrated at Popponesset Spit system along the southern coast of Cape Cod. Spit breaching is facilitated when erosion has narrowed and vertically lowered the profile of the barrier ...

Perhaps the navigation channels dredged in the open bay area near the present inlet in 1916 and 1936 contributed to creating this hydraulically efficient conduit to carry the water from the bay back to the ocean. Today, dredging of a navigation channel near the base of the spit leading to the bay and inlet (near Popponesset Island) may be creating a similar conduit to flow. This scenario will be addressed in the analysis section.

In summary, Popponesset Spit has been breached near Popponesset Island, Little Thatch Island, and west of Big Thatch Island as indicated in Table 1. Only the 1954 breach has remained as a permanent inlet. All other breaches healed themselves within 5 to 10 years. What may have transpired after more recent breaches (1978 and 1991) is not known because the openings were promptly closed with fill material by local interests. Because the spit is narrower and lower, overwash is occurring more frequently. The channel between Popponesset Island and the spit is in a fixed location, further limiting the width of the spit. These factors contribute to the likelihood of breaching of Popponesset Spit.

Water Level (Storm Surge)

As indicated previously, storms cause a major portion of the landward migration of Popponesset Spit and are therefore a significant aspect of the evolution of the spit. With storms come a rise in the mean water level due to: (a) wind stress on the water surface and (b) in the case of hurricanes (and northeasters to a lesser degree), the reduction in atmospheric pressure. The effect of an elevated water level is to bring wave activity onto portions of the beach that are normally not exposed to such processes (Aubrey and Gaines 1982a). Water levels for the 1938, 1944, and 1956 hurricanes, Hurricane Carol ('54), Hurricane Donna ('60), Hurricane Bob ('91), the Blizzard of '78, and the Halloween northeaster ('91) as well as for 1-, 10-, 50-, and 100-year return period events are given in Figure 8. At least one storm with winds over 32 mph occurs annually, raising water levels and allowing larger waves to reach or overtop the submerged spit (U.S. Army Engineer Division, New England 1972). Sand is then transported into the inlet by waves and is also carried over the barrier beach into the bay, filling navigation channels and covering shellfish beds. The blizzard of '78 (U.S. Geological Survey 1979) and the '38 hurricane (U.S. Army Engineer Division, New England 1988) had surge levels of 5.8-6.0 ft NGVD, which is equivalent to a 10-year event. Both of these storms caused breaching of Popponesset Spit. The 1938 storm occurred when the beach cross section was much more substantial, the spit extended further to the northeast (to Rushy Point Pond), and groins were not present on the downdrift beaches. Still, a breach occurred from this 10-year event and ultimately healed itself. Although the 1978 cross-sectional profile is not available, it can be surmised that the cross section was somewhere between the 1966 and 1991 cross sections. What is important is that, again, a 10-year event caused breaching of Popponesset Spit. In 1991, Hurricane Bob and the Halloween northeaster occurred within 2 months of each other. Hurricane Bob had a surge level of 3-4 ft NGVD. A 30-ft-wide breach developed near Popponesset Island and flooding occurred in many of the homes along Popponesset Bay and Popponesset Island. Local residents hired a contractor to fill the breach; therefore, its natural evolution is not known.

Runup

Another factor in the analysis of spit evolution is the amount of runup on and overtopping of Popponesset Spit. The limit of runup defines the zone of possible wave damage (Douglass 1990). Following Resio's (1987) method, the maximum runup for given incident wave conditions can be estimated. To obtain an estimate of wave conditions, wave data at WIS Station 86 were reviewed (Hubertz et al. 1992). The yearly mean wave height is 3-5 ft (1-1.5 m); therefore, a wave height of 3 ft was selected. A range of wave periods from 6 to 10 sec were analyzed and a storm duration of 1 hr was assumed. Resio (1987) uses the storm duration and period to determine the number of waves (assumed to be equivalent to runup events) during the storm and then calculates the probability of exceedance of the maximum runup during the storm. The best estimate of the beach slope from a September 1992 site inspection was 1:10 to 1:5. From Resio's formula, elevation of runup on a 1:10 slope was computed to be 2-3 ft and runup on a 1:5 slope was computed as 5-6 ft. With a 1-year surge level of 3.7 ft NGVD and a peak spit elevation of 6.0 ft NGVD, this estimate of runup using the yearly mean wave height would be sufficient to overtop the spit (considering that the addition of setup would possibly increase the water level slightly). When the vertical elevation of runup exceeds the berm crest elevation, overwash occurs.

Overwash

Overwash is the transfer of beach sand across to the lagoonal side of a barrier island through sluiceways during hurricanes or other violent storms (Shepard and Wanless 1971). Aerial photographs often reveal locations and boundaries of overwash events. For example, the 1938 aerial photograph shows a breach at Popponesset Island and a washover fan in that vicinity. Overwash typically affects a barrier on a geologic time scale since it depends largely on long-term factors such as sea-level change, sediment availability, and storm climatology (Leatherman 1981). However, in the case of Popponesset Spit, more frequent (smaller) storm events are capable of overwashing the barrier due to its reduced peak elevation as was discussed in a previous section.

Overwash events tend to roll material over a barrier island or spit and the entire feature attempts to migrate landward. Overwash is defined by Leatherman (1981) as any swash surge that passes over the "crown" (or berm) of the barrier beach. As material overwashes and shears off the berm or "crown," overwash occurs more and more frequently. Popponesset Spit is very uniform in elevation and profile shape, indicating considerable overtopping and overwashing has shaved the spit down rather uniformly. There are no significantly high or low areas on the entire spit. It is concluded that overwash is an important factor in barrier dynamics since this process can effectively move an island landward in space and time (Leatherman 1981).

Longshore Transport

Three definitive statements that can be made about longshore transport at Popponesset Spit are:

a. Net longshore transport is to the northeast based on examination of aerial photographs which show (1) an offset to the northeast in every groin pocket, and (2) a long-term trend of spit elongation in the northeast direction.

b. Groins constructed in the 1950's are limiting sediment supply to the spit indicated by the marked notching at the spit base in the last

40 years. The quantity of sand denied to Popponesset Spit by the groins is estimated by Aubrey and Gaines (1982b) to be 3,000 to 4,000 cu yd/year. However, sediment is likely to bypass the groins during storms when the surf zone is much wider. Indications of littoral drift are the large ebb and flood tidal shoals observed at low tide. These features signify that sediment is moving into and out of the inlet by littoral drift processes at the expense of the spit. (The spit has lost a considerable volume of sediment considering the changes in elevation and width that occurred between 1966 and 1991.) The growth of the ebb and flood deltas is due to deposition of littoral material from the spit, and hence, is a factor in the spit's reduced volume.

c. The orientation of the spit is to the northeast and the predominant wave direction is from the south. As the spit continues to rotate in a counterclockwise direction, waves break at a more oblique angle to the shoreline, resulting in a greater rate of longshore transport. As time passes, longshore transport rates are probably accelerating along Popponesset Spit (assuming the incident wave climate is stationary).

3 Inlet Stability Analyses

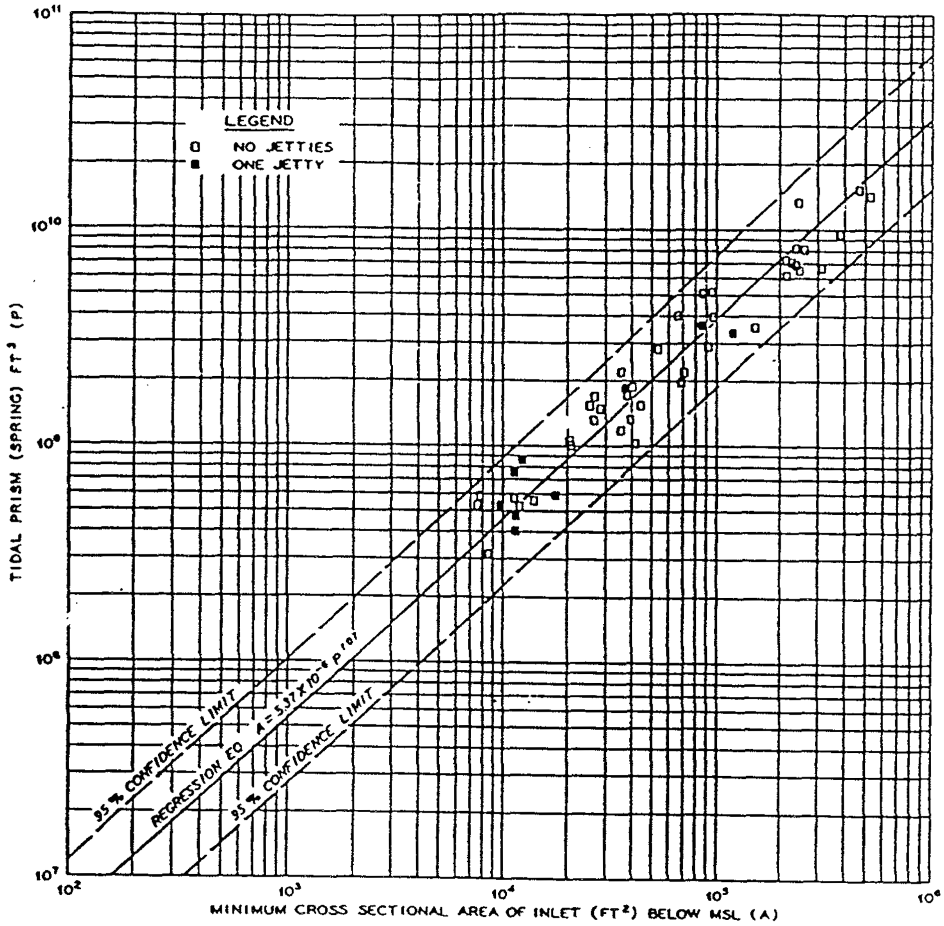
An inlet stability analysis was performed to assess the stability of the existing inlet and the potential challenge created when a new inlet (breach) forms. Examination of inlet stability involved study and application of several analysis methods. O'Brien (1931) proposed that the minimum cross-sectional area of an inlet is controlled by the tidal prism. The stable (or equilibrium) cross-sectional area of an inlet A_e is related to the tidal prism P by the following relationship

$$A_e = 4.69 \times 10^{-4} P^{.85} \tag{1}$$

This relationship gives an appropriate order of magnitude estimate of inlet cross-sectional area. O'Brien (1966) revisited this relationship and derived two relationships for inlets with and without jetties.

Jarrett (1976) separated O'Brien's data sets for the Atlantic, Gulf, and Pacific coasts to determine if different (A_e versus P) relationships existed for different coastlines of the United States. For unjettied and single-jettied inlets, Jarrett found that O'Brien's formulae could be modified slightly. Following Jarrett (1976), the minimum cross section (to mean sea level) for Popponesset Inlet was determined to be 1,800-2,200 ft^2. The tidal prism was computed to be 1.2×10^8 ft^3 based on a bay area of 665 acres and a spring tide range of 2.8 ft. Plotting the range of points on Jarrett's tidal prism versus cross-sectional area curve (Figure 13) shows that the existing inlet to Popponesset Bay is in equilibrium. However, the tidal prism and cross-sectional area for this analysis are smaller than any of the inlet data points used to establish Jarrett's equilibrium equation (curve). There is a more recent study for smaller inlets which suggests that the relationship between tidal prism and inlet area may be different for smaller inlets; however, the 14 inlets studied were confined to the lower Chesapeake Bay (Byrne, Gammisch, and Thomas 1980).

Escoffier (1940) proposed a method of investigating the stability of an inlet based on the maximum inlet velocity for different cross-sectional areas. In this method, a bell-shaped curve of cross-sectional area A_c versus maximum velocity V_{max} is constructed for a given inlet. A sample curve (Figure 14) shows the delineation between stable and unstable inlets (Czerniak 1977). The cross-sectional area corresponding to the peak value of velocity is called the



NOTE: REGRESSION CURVE WITH 95 PERCENT CONFIDENCE LIMITS.

TIDAL PRISM VS
CROSS-SECTIONAL AREA
INLETS ON ATLANTIC COAST
WITH ONE OR NO JETTIES

Figure 13. Tidal prism versus cross-sectional area from Jarrett (1976)

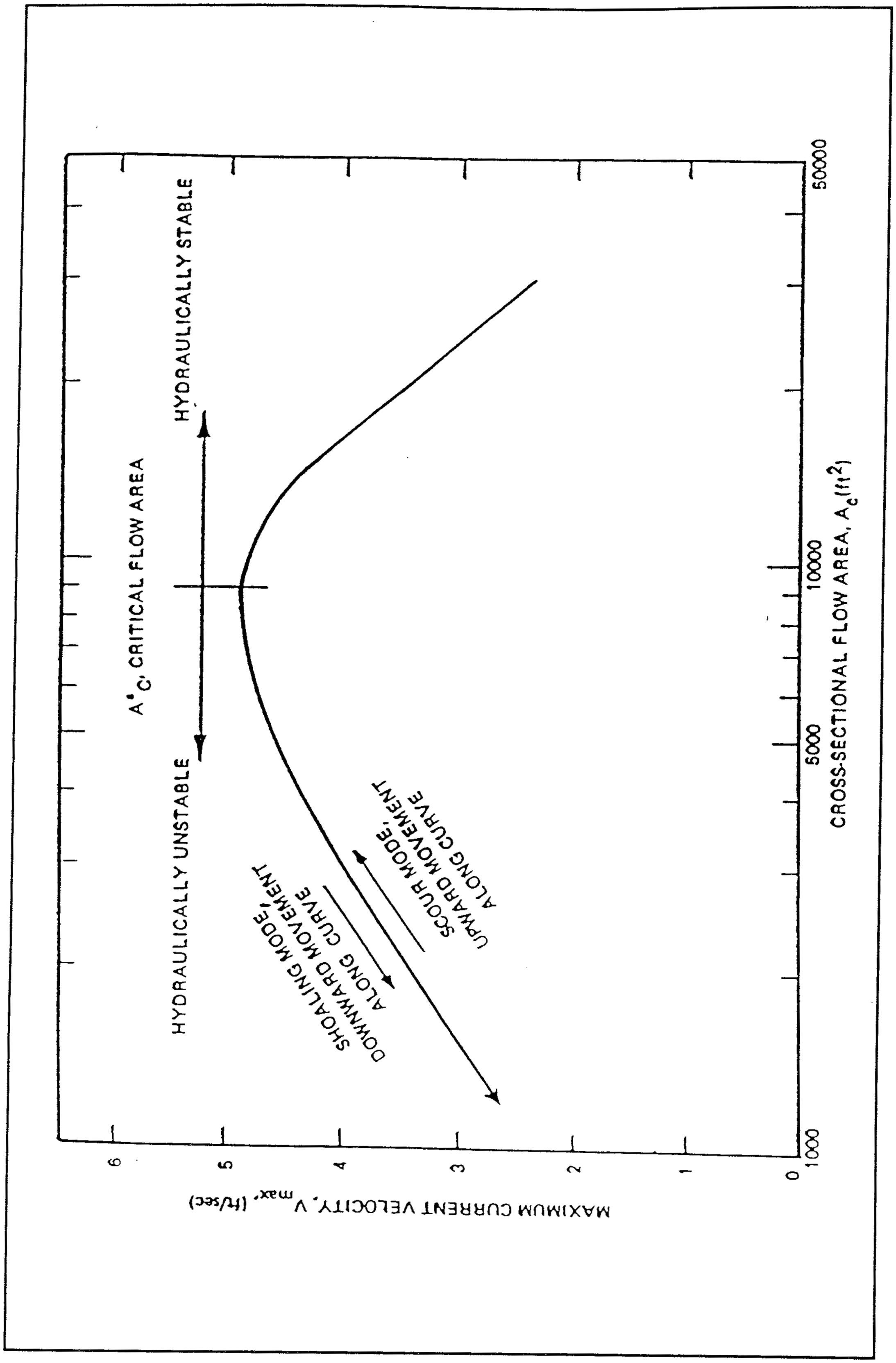


Figure 14. Escoffier diagram

critical area A^*_c. A change in cross-sectional area from the critical value will cause a change in the sediment flow capacity of the system, resulting in greater erosion or deposition rates (Skou 1990). For example, if a storm caused additional littoral drift material to enter the inlet and the cross-sectional area falls below A^*_c (left portion of the curve), then the sediment flow capacity will be reduced. Additional sediment will be deposited because the flow can no longer remove the same amount of material as before and the inlet will eventually close. On the other hand, if the cross-sectional area is greater than A^*_c, the inlet is considered stable. Small changes in the cross-sectional area will be balanced by an opposing process, keeping A_c in a narrow range (Skou 1990). As shown below, Popponesset Inlet is on the stable limb of the curve constructed for this inlet.

The method of construction of the curve for a particular inlet is to allow the cross-sectional area of the inlet to vary and the maximum velocity is determined for each cross section. For the inlet to Popponesset Bay, the inlet area A_c was varied over the range 300-2,200 ft^2. The following values were assumed for Popponesset Inlet:

Channel length (L)	1,000 ft	Tidal period (T)	12.42 hr
Entrance loss (k_{en})	0.1	Bay area (A_b)	665 acres
Exit loss (k_{ex})	1.0	Tidal amplitude (a_s)	1.4 ft
Friction (F)	$k_{en}+k_{ex}+fL/4R$	Hydraulic radius (R)	variable
		Gravitational acceleration (g)	32.2 ft/sec^2
		Darcy-Weisbach friction factor (f)	variable

From Equations 4-65 and 4-66 (*Shore Protection Manual* (SPM) 1984), values for the friction coefficent K_1 and the frequency coefficient K_2

$$K_1=\frac{a_s A_b F}{2LA_c} \tag{2}$$

$$K_2=\frac{2\pi}{T}\sqrt{\frac{LA_b}{gA_c}} \tag{3}$$

were determined. Using the values of K_1 and K_2 and Figure 4-75 (SPM 1984), a value of dimensionless maximum velocity V'_m was determined. Equation 4-64 (SPM 1984)

$$V'_m = \frac{A_c T V_m}{2\pi a_s A_b} \tag{4}$$

was then solved for the maximum velocity V_m. All (A_c, V_m) points were plotted to determine the stability curve for Popponesset Inlet (Curve 1 in Figure 15). Popponesset Inlet is on the right limb of the curve and is therefore considered stable based on engineering estimates of cross-sectional area, channel length, and other parameters. However, conditions at the base of Popponesset Spit and the likelihood of breaching are not considered in this analysis. If a second inlet opened near Popponesset Island, the likelihood of the new inlet capturing the tidal prism of the existing inlet would have to be determined. This would require a numerical modeling effort.

The second curve in Figure 15, sometimes referred to as the equilibrium curve, was constructed from Jarrett's formula and Escoffier's (1977) formula. With a cross-sectional area A_c of 2,200 ft^2, Jarrett's formula for non-jettied Atlantic coast inlets was solved for the tidal prism:

$$2200 = A_c = 5.37 \ x \ 10^{-6} P^{1.07} \tag{5}$$

or

$$P = 1.117 \ x \ 10^{8} ft^{3} \tag{6}$$

Next, Escoffier's formula was solved for various cross-sectional areas:

$$V_m = \frac{\pi P C}{A_c T} \tag{7}$$

The dimensionless number C is a function of Keulegan's K and reflects the filling of the bay area. That is, large values indicate that the bay is filling completely, meaning the inlet is hydraulically efficient or the bay is small. Again, all (A, V_m) points were plotted in Figure 15. The intersection of the two curves indicates the equilibrium area for Popponesset Inlet. From this analysis, it has been shown that the present inlet is stable based on engineering estimates of inlet parameters. However, should a breach develop near Popponesset Island, the stability of the existing inlet would be challenged. In all probability, the bay could not support two inlets and the more hydraulically efficient inlet would dominate. The less efficient inlet would eventually close. Some factors that would determine the hydraulic efficiency of the two openings include the width and depth (cross section) of the breach and inlet and the amount of dredging performed in the vicinity of each opening.

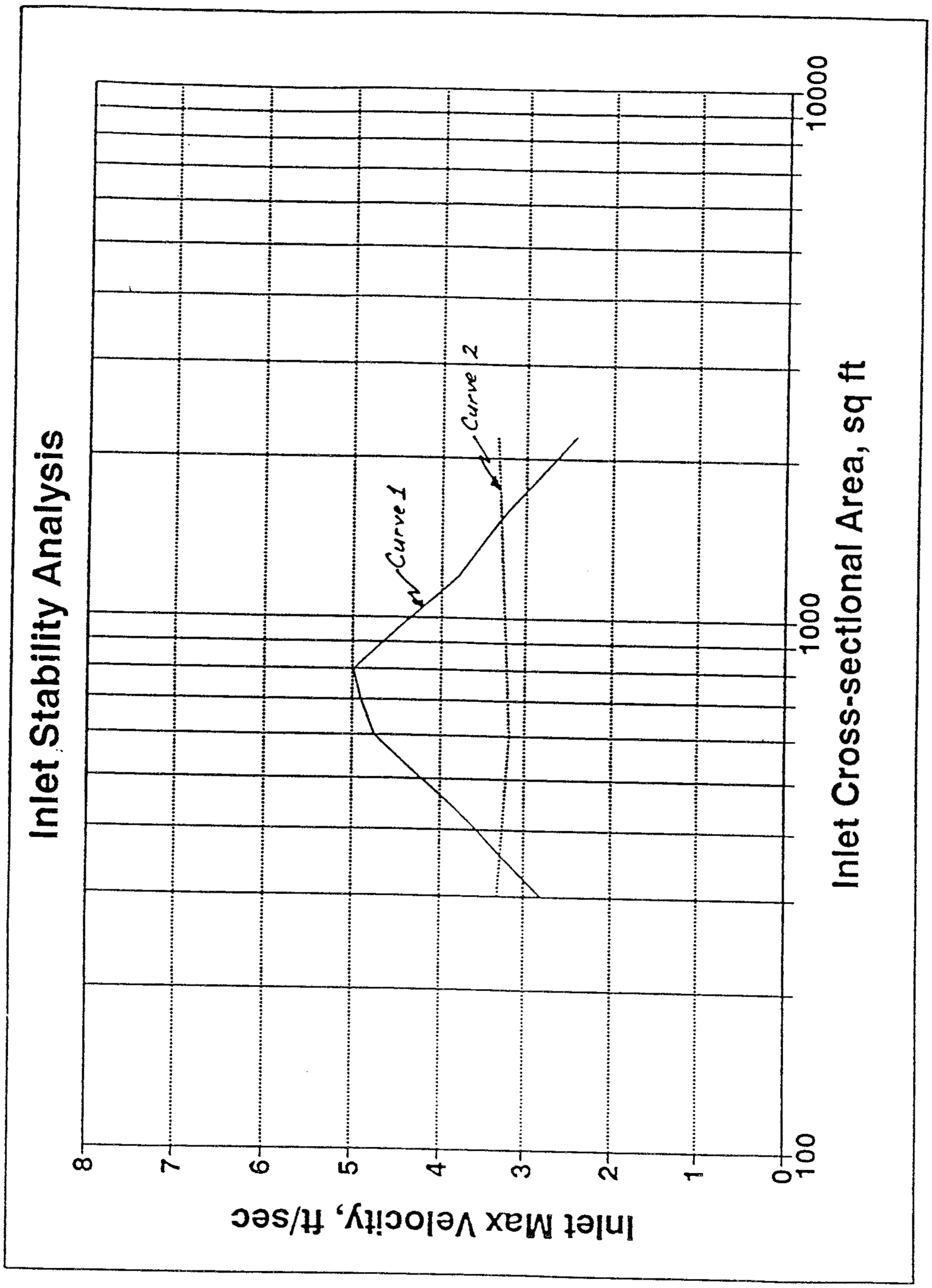


Figure 15. Inlet stability curve for Popponesset from Czerniak (1977)

4 Modes of Spit Deterioration and the Impacts on Popponesset Bay

Popponesset Spit is experiencing severe degradation. The entire spit has low relief (the peak spit elevation is approximately 4-5 ft NGVD) and overwash is likely to occur over a major portion of the spit on an annual basis. The width of the spit has also decreased, with the most dramatic change at the base of the spit near Popponesset Island. The beach width was approximately 250 ft in 1966 and now measures 70-80 ft at the base of the spit. Potentially two modes of deterioration are operating on Popponesset Spit: (a) slow degradation in elevation of the entire spit, and (b) a breach of the spit, possibly resulting in a new inlet. Both modes have the potential to cause additional damage to property within the bay.

Deterioration of the first type (slow degradation) will continue to expose the entire shore of the back bay to increased levels of wave attack during storms that overtop the spit. A given storm water level that overtops the spit will transmit greater amounts of wave energy to the bay as the island degenerates (lowers) if one assumes the broken wave energy transmitted across an overtopped spit is proportional to the water depth (a reasonable first order assumption). For storms that do not inundate the spit, waves impacting the interior shoreline are locally generated within the bay. When the spit is inundated, the interior bay shoreline is exposed to ocean waves that have greater periods and wave heights (i.e. more energy), and the local wind can add to the growth of the waves within the bay. The increased exposure to more energetic wave action will produce more damage from direct wave impact and increased likelihood of cliff/bluff failure.

Storm wave damage from Hurricane Bob and the 30 October 1991 storm is clearly evident in photographs and discussions with local residents (Bennett E. Gordon, Jr.[1], Chairman, Mashpee Waterways Commission). Accounts of damage to Half Tide Marina and properties in the upper portion of Popponesset Bay provide explicit evidence of storm wave attack. Although the storm

[1] Personal Communication, 1 September 1992, Bennett E. Gordon, Jr., Chairman, Mashpee Waterways Commission, Mashpee, Ma.

surge level for Hurricane Bob was reported to be 3-4 ft NGVD (U.S. Army Engineer Division, New England 1992) and the peak spit elevation was 6 ft NGVD in 1991 (Grotzke[1]), photographs from Dr. Gordon show positively that total overwash of the entire spit occurred during Hurricane Bob and the October 1991 storm. It should be noted that major portions of the spit were well below the 1991 surveyed "peak" elevation and further deterioration of the spit after the 1991 survey likely occurred. From a 1992 walking tour, the highest elevation observed along the entire spit is estimated to be approximately 4-5 ft NGVD. It is concluded that deterioration mode No. 1 (slow degradation) led to overtopping of the spit, and ocean storm waves attacked and damaged the interior shoreline of Popponesset Bay.

If the spit continues to diminish in elevation, any given storm that overtops the spit will be capable of allowing a greater amount of wave energy to propagate into Popponesset Bay. In addition, overwash would occur with increasing frequency (smaller storms). Less severe storms will overtop the spit as the peak elevation diminishes. Again, storm wave attack and flooding would impact the entire interior bay area behind the diminishing barrier spit.

If the barrier continues to lower in a slow degradation process (without a breach), then water quality and navigation will be impacted. Overwash material deposited in the navigation channel at the southern tip of Popponesset Island would limit or block navigation to and from Popponesset Creek. Without a breach, closure or blockage of the navigation channel could contribute to degradation of water quality in Popponesset Creek as has occurred in the past. Problems with water quality and navigation will probably occur with greater frequency as the spit continues to deteriorate.

Deterioration of the second type (breaching) will produce damages primarily to the properties immediately adjacent to the breach, if a permanent breach develops. If a breach occurs at the base of Popponesset Spit, properties at the end of Popponesset Island will probably be subjected to increased erosion due to currents and exposure to ocean waves that propagate through the new entrance. A breach should not significantly alter flood levels in the back bay. The wave climate in the back bay should not be altered by a breach except in the immediate vicinity of the breach.

The most likely location for a breach is at the base of the spit because of the narrow width and low elevation. Should a breach occur at the base of Popponesset Spit, the existence of a dredged channel at the southern tip of Popponesset Island may serve to channelize flow to and from the breach and challenge the existing (stable) inlet.

A breach of Popponesset Spit is likely to occur in conjunction with a storm event, probably in the next 10 years and possibly in the next 2 to 5 years. Most past breaches have healed themselves; however, recent breaches were

[1] Personal Communication, 1 September 1992, Michael H. Grotzke, Director of Engineering, New Seabury Company Ltd., New Seabury, MA.

closed by local residents and it is not known how they may have evolved if left to evolve naturally. Although a dual inlet analysis was not performed in this study, it seems unlikely that the system can support two inlets and one would naturally close. Without further analysis (involving modeling) it is not clear which inlet would dominate, in light of the fact that the dredged channel near the base of the spit may capture flow from the existing inlet.

A breach of Popponesset Spit near Popponesset Island would have a direct impact on navigation and water quality in Popponesset Creek and Popponesset Bay. A breach near Popponesset Island would provide a shorter path to Nantucket Sound, but navigating the breach could be difficult until the cross section stabilizes with adequate clearance. If a breach near Popponesset Island begins to establish itself, navigation in the present inlet may become impaired, creating the situation of two non-navigable inlets. A significant breach would increase tidal flushing, which may improve water quality in Popponesset Creek and the western portion of Popponesset Bay. The influence of a breach on the channel along the northern side of Popponesset Island and the stability of approaches to Popponesset Island Bridge are not known.

In summary, surge and waves propagating through a breach at the base of Popponesset Spit would impact the homes on and around Popponesset Island (a localized effect). The increased flow through the breach could cause increased local erosion, and storm wave attack could cause significant damage to properties in the immediate area as occurred during Hurricane Bob. Flooding of homes was evident from that storm (Bennett E. Gordon, Jr.[1], Chairman, Mashpee Waterways Commission). In addition, seawalls erected near homes on Popponesset Islands sustained damage, as did the Popponesset Island Bridge.

Neither slow degradation nor breaching should greatly influence the 100-year flood level, or other flood levels; however, this could be evaluated with a simple hydrodynamic model. The shape of the hydrographs may change somewhat and the influence of the deteriorated spit on faster moving hurricanes and northeasters may be somewhat different. More importantly, mode No. 1 deterioration (slow degradation) of the spit will result in increased wave action that occurs in conjunction with the flood levels, and the spit will be inundated by less severe storms. This is the critical point from the standpoint of damage to the interior bay shoreline. Again, mode No. 2 deterioration (breaching) has a more localized impact and potential for damage.

[1] Personal Communication, 1 September 1992, Bennett E. Gordon, Jr., Chairman, Mashpee Waterways Commission, Mashpee, Ma.

5 Possible Solutions

The most immediate need is a more effective barrier along the spit to prevent increased storm wave action in the back bay. A more substantial beach berm (width and elevation) will reduce the likelihood of overwash from storms and the potential for spit breaching. Removing the groins will not provide much sediment based on the low estimate of longshore transport (Aubrey and Gaines 1982b); therefore, this is not a recommended option. Additionally, these groins are likely to be bypassed during storms when the surf zone is wider. The groin nearest to the spit appears larger than the others and the groin pocket is slightly less full. Removal of this groin would probably just shift the anchor point of the spit further west to the next groin and that location would experience increased erosion. Beach nourishment could provide immediate protection to the spit from overwash and is considered a suitable means of storm protection. Due to the predominance of northeasterly drift, a terminal groin may be desirable to contain the fill and reduce losses and shoaling in the entrance channel; however, a terminal groin may conflict with provisions of the National and State Coastal Barrier Resources Act. Possible borrow sources for sand are the large ebb and flood tidal shoals which are exposed at low tide. Vegetation planted in conjunction with beach nourishment may reduce the intensity of overwash during extreme events and thereby help to stabilize the spit. However, one environmental concern is the protected nesting area at the tip of Popponesset Spit which may prohibit placement of sand and vegetation on that portion of the spit.

Another factor that has weakened the local integrity of the spit and potentially contributes to the likelihood of a breach is the navigation channel dredged at the southern end of Popponesset Spit. The channel pins the landward migration of the spit (causing narrowing) and might serve as a conduit for flow should a breach develop. A possible solution is to allow the channel to fill and dredge a navigation channel north of Popponesset Island. This would also require construction of a new bridge to Popponesset Island and approaches to Popponesset Creek that would allow boats to pass. This solution would also eliminate the need for increased maintenance of the existing channel at the southern end of Popponesset Island that will probably be needed as the frequency of overtopping increases.

6 Additional Work Needed

To develop a more complete picture of coastal processes in the vicinity of Popponesset Spit and aid in the design of any solutions to problems occurring there, more information is needed. Crucial data missing in the analysis process include beach profiles along the spit, inlet geometry (cross sections and channel length), inlet velocities, details of breach closures, local wave conditions in Nantucket Sound during storm and non-storm conditions, and knowledge of longshore transport rates. In each case, some information was available which allowed for an educated guess about the particular feature or process, but additional data would be beneficial to future studies.

One aspect of the study that requires additional efforts is the impact of a breach on the existing inlet and bay system. That is, which inlet would be more hydraulically efficient and would dominate? Could Popponesset Bay support two inlets? These questions could be easily addressed with an inlet hydrodynamic model such as DYNLET1 (Amein and Kraus 1991). Using the modeling tool, a second inlet (breach) could be "opened" and various cross sections could be tested to determine the amount of flow through each inlet and assessments of inlet stability under different conditions could be made. Such a tool also could be used to quickly investigate the influence that breaches might have on surges in the back bay.

Another question that was not answered in this study is the relationship between storm waves and surge and the process of barrier island erosion and overwashing. What type of storms produce conditions that promote spit degradation? A storm-induced beach profile change model, along with collection of field data, could be used to address this question and aid in the design of a protective berm. Additional studies should be performed to investigate the amount of energy that can propagate into the bay under degraded spit conditions.

7 Summary and Conclusions

Popponesset Spit has undergone significant change during the past two centuries including growth and attrition in length, landward migration and rotation, narrowing, diminished elevation, and opening and closing of breaches. The spit is migrating landward and rotating about its base in a counterclockwise direction. The spit rotation stems from the fact that the groin at the base of the spit anchors the shoreline, pinning its location. Landward migration is dominated by major storms and the long-term landward migration occurs at a slower rate. The peak elevation of the spit has been reduced dramatically indicating that a less severe storm can now completely submerge the spit. Storms cause a major portion of the landward migration of Popponesset Spit and are therefore a significant aspect of the evolution of the spit. The width of the spit has also decreased significantly. Maintenance of a navigation channel between Popponesset Spit and Popponesset Island limits any further landward movement of the bay-side shoreline of the spit in this region. With the bay-side boundary pinned and the seaward boundary moving landward, thinning of the spit is inevitable.

Popponesset Spit is very uniform in elevation and profile shape, indicating that considerable overtopping and overwashing have shaved the spit down rather uniformly. There are no significantly high or low areas on the entire spit. It is concluded that overwash is an important factor in the dynamics of this barrier spit.

An indication of littoral drift is the large ebb and flood tidal shoals observed at low tide. These features signify that sediment is moving into the inlet by littoral drift processes at the expense of the spit. (The spit has lost a considerable volume of sediment considering the changes in elevation and width that occurred between 1966 and 1991.) The growth of the ebb and flood deltas is due to deposition of littoral material from the spit and hence, is a factor in the spit's reduced volume. However, it is likely that the greater volume is lost due to overwash.

Popponesset Inlet is on the stable limb of Escoffier's inlet stability curve and is therefore considered stable based on engineering estimates of cross-sectional area, channel length, and other parameters. However, the stability of a breach at the base of Popponesset Spit was not considered in this analysis. If a second inlet opened near Popponesset Island, the likelihood of the new inlet capturing the tidal prism of the existing inlet would have to be determined. This would require additional study involving a numerical modeling effort.

A breach of Popponesset Spit is likely to occur in conjunction with a storm, certainly with a 10-year event and possibly with as little as a 2- to 5-year event. Most past breaches have healed themselves; however, recent breaches were closed by local residents and it is not known how they may have evolved. Should a breach develop near Popponesset Island, the stability of the existing inlet would be challenged. Although a dual-inlet analysis was not performed in this study, it seems unlikely that the system can support two inlets and one would naturally close. Without further analysis (involving modeling) it is not clear which inlet would dominate, in light of the fact that the dredged channel near the base of the spit may help capture flow from the existing inlet. Some factors that would determine the hydraulic efficiency of the two openings include the width and depth (cross section) of the breach and inlet and the amount of dredging performed in the vicinity of each opening.

A breach of Popponesset Spit near Popponesset Island would have a direct impact on navigation and water quality in Popponesset Creek and Popponesset Bay. A breach near Popponesset Island would provide a shorter path to Nantucket Sound, but navigating the breach could be difficult until the cross section stabilizes. If a breach near Popponesset Island begins to establish itself, navigation in the present inlet may become impaired, creating the situation of two non-navigable inlets. A significant breach would increase tidal flushing, which may improve water quality in Popponesset Creek and the western portion of Popponesset Bay. However, it would put erosional pressure on adjacent property due to increased currents and exposure to wave attack from the ocean.

If the barrier continues to lower in a slow degradation process (without a breach), then water quality, navigation, and storm protection would be impacted. Overwash would occur with increasing frequency (smaller storms). Even without a breach, water quality in Popponesset Creek would be diminished as has occurred in the past due to blockage of the navigation channel. Obviously, navigation would also be impaired. If the spit continues to diminish in elevation, more wave energy will propagate into Popponesset Bay when severe storms overtop the spit. Areas behind the spit would be exposed to increasing wave attack and flooding caused by more frequent events. As the spit degrades to lower and lower elevations, it may begin to break up (several breaches may form) and eventually contribute to shoaling in the navigation channels.

A more substantial berm (width and elevation) will reduce the likelihood of overwash from storms and the potential for spit breaching. Beach nourishment will provide immediate protection from overwash and is considered a suitable means of storm protection. Due to the predominance of northeasterly drift, a terminal groin may be desirable to contain the fill and reduce losses and shoaling in the entrance channel; however, a terminal groin may conflict with provisions of the National and State Coastal Barrier Resources Act. Possible borrow sources for sand are the large ebb and flood tidal shoals which are exposed at low tide. Vegetation planted in conjunction with beach nourishment may reduce the intensity of overwash during extreme events and thereby help to stabilize the spit.

Another factor that has weakened the local integrity of the spit and potentially contributes to the likelihood of a breach is the navigation channel dredged at the southern end of Popponesset Spit. The channel pins the landward migration of the spit and also serves as a conduit for flow when a breach develops. A possible solution is to allow the channel to fill and dredge a navigation channel north of Popponesset Island. This would also require construction of a new bridge to Popponesset Island and approaches to Popponesset Creek under which boats could navigate. Additional studies could be conducted to evaluate the effectiveness of these measures.

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13. ABSTRACT *(Maximum 200 words)*

Popponesset Beach is an approximately 1-mile-long barrier beach (or spit) fronting Popponesset Bay located on Nantucket Sound in Mashpee, Cape Cod, Massachusetts. Popponesset Spit has experienced dramatic changes in the last 40 years, beginning with a major breach in 1954, which resulted from a series of hurricanes (Carol, Edna, and Hazel). Breaches near Popponesset Island, Little Thatch Island, and Big Thatch Island were observed at various times between 1892 and 1991.

The main purpose of the study was to determine the likelihood of a breach of Popponesset Spit and the impact (in terms of water quality, storm protection, and navigation) of breaching and/or slow degradation of the spit on Popponesset Bay. A review of historical information pertaining to the evolution of Popponesset Spit and an analytical/empirical "desktop" analysis were performed.

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